A Radioisotope Powered Cryobot for Penetrating the European Ice Shell

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Abstract. The Cryobot team at JPL has been working on the design of a Cryo-Hydro Integrated Robotic Penetrator System (CHIRPS), which can be used to penetrate the Mars North Polar Cap or the thick sheet ice surrounding Jupiter's moon, Europa. The science for either one of these missions is compelling. For both Mars and Europa the major scientific interest is to reach regions where there is a reservoir of water that may yield signs of past or extant life. Additionally, a Mars polar cap penetration would help us understand both climatic and depositional histories for perhaps as far back as 20 million years. Similarly, penetration of the Europa ice sheet would allow scientists to unravel the mysteries surrounding the thick ice crust, its chemical composition, and subsurface ocean properties. Extreme mass and power constraints make deep drilling/coring impractical. The best way to explore either one of these environments is a cryobot mole penetrator vehicle, which carries a suite of instruments suitable for sampling and analyzing the ice or ocean environments. This paper concentrates on a Europa deep ice (i.e., kilometers) application of the CHIRPS, and introduces the reader to the vehicle design with focus on the use of radioisotope thermoelectric generator (RTG) technology as the primary heat (1Kw total) and power source for the robotic vehicle. Radioisotope heater unit (RHU) milli-watt power systems (120mw total) are also employed to power the mini-radiowave ice transceivers, which are used to relay data through the ice up to the surface lander. The results of modeling and design work for both of these areas are discussed in this paper. Although radioisotope power is baselined for the Europa flight version of the cyrobot, no decision on the final design of the cryobot will be made until the environmental review process is complete. Any use of the cryobot for Mars or Europa will conform to all environmental and planetary protection requirements.

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1. PROBLEM DESCRIPTION

Galileo images of Europa show signs of fracturing and upwelling of material similar to that experienced in the sheet ice in Antarctica. Other areas with smoother surfaces are indicative of resurfacing/freezing of liquid water [1]. Cratering data [2] suggests that the smooth interior of the depressions were caused by liquid refilling/freezing after impact. Ice ridges and lateral fractures caused by crustal fracturing and butting [3] not only suggest on-going crustal dynamics but also indicate, perhaps, areas where the ice crust is thinner than previously predicted. In the absence of direct empirical data, it is clear that in order to develop appropriate technology to support a landed robotic penetrator mission we must be conservative in our assumptions about the dynamics of the ice environment. Understanding that a deep ice penetration equates to the order of 10-km range, tether based power and communication between the surface lander and cryobot is not practical due to the obvious presence of large internal shear forces. Additionally, severe packaging and mass constraints require that a very small diameter tether be employed—another limiting strength factor. Finally, the same packaging and mass constraints prevent the cryobot from being able to carry and pay-out several kilometers of tether.

Based on the above environment and constraints, it became obvious that any deep ice penetrating robotic vehicle must carry its own power source, and must communicate with the lander without a tether. Solar array power on Europa is impractical due to its distance from the Sun. In-situ fuel production based on carbon, oxygen, and hydrogen requires a substantial energy source to drive the reaction, and, is therefore also impractical. Since high energy density battery technology for extreme cold environments is not close to being available and is too inefficient for a 2005 technology freeze in order to support a 2008 mission, the only remaining viable energy source is radioisotope [4]. Given this conclusion, the problem addressed by the cryobot team was: "How much thermal/electrical power do we need to initiate and sustain ice penetration, control the vehicle, operate the in situ science instruments, and communicate vehicle state data and science data back to the lander on the surface?" This was followed by: "Can we develop a vehicle and communication system design utilizing radioisotope technology already in development to allow us to meet a near horizon technology cut-off date, and which accommodates the likely form this thermoelectric energy will take?" The following sections answer both of these questions.

2. OVERVIEW OF CHIRPS DESIGN/OPERATION

A. Basic Vehicle Design

The preliminary CHIRPS mole penetrator design is shown in Figure 1. The complete vehicle is 1 m in length, 15 cm in diameter, 25–30 kg, and operates off 1 Kw thermal of RTG energy. The vehicle has a slight taper to enable the re-freezing melt jacket to impart a slight downward force on the probe. Electronics, actuators, communication, and science instruments operate off 40–60w of thermoelectric power. The vehicle is totally self-contained in that it carries its own power, a full suite of state sensors, on-board computing/control, an in situ science instrument suite, and a communication link. Figure 1 shows the mole penetrator composed of essentially 5 major subsystems [5]:

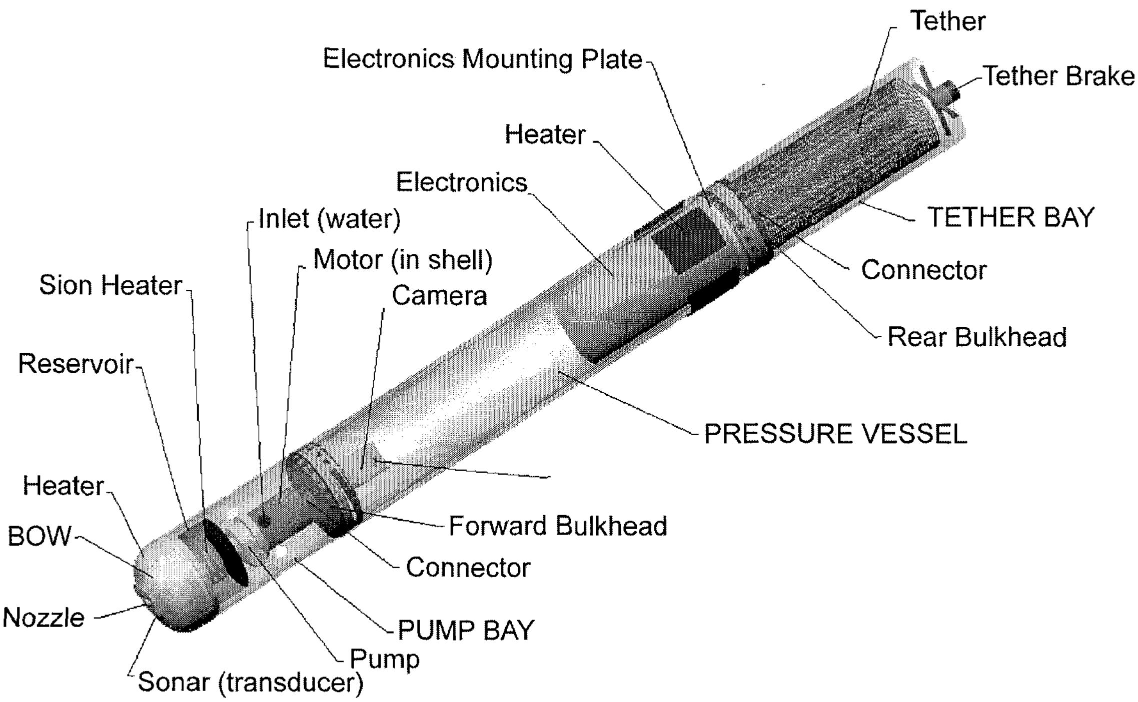


FIGURE 1. Preliminary CHIRPS mole penetrator design.

1. **Nose:** The CHIRPS nose is composed of four quadrant heaters, which are separated by a ceramic insulating divider. This divider allows the heaters to be differentially activated. By turning heaters on one side of the nose, while shutting heaters off on the opposite side, the vehicle can be steered. The current design calls for an internal micro-fluid loop to move heat to the different external shell surfaces to initiate melting and mobility rather than resistance heaters. This is because thermoelectric conversion efficiency will not allow sufficient thermal energy for the phase-change melt process to be generated by the electric heaters. The nose also contains a downward looking acoustic transmitter/receiver for imaging obstacles and the ice-ocean interface. The cryobot team has been experimenting with water-jetting as a means of melting and managing debris which might reduce the heat transfer efficiency at the melt-front. It is not clear yet to what extent the Europa ice contains sediment/impurities. However, sufficient volume is available to also incorporate a small water-jetting system which draws in melt-water from the melt jacket around the shell, heats it with the RTG waste heat, and pumps it back out through the nose (see avionics bay below).

2. **Power Bay:** The power bay contains four RTG bricks baselined at 250w thermal each. The thermoelectric converters and micro-fluid loop are attached to the sides of the bricks. The current design has the bricks aligned serially to allow the aft science instruments and vehicle control avionics to only see particle flux from essentially one brick. Particle flux modeling for the instrument bay showed that "centimeter" scale set back from the bulkhead was sufficient to protect the instruments from radiation [5]. This was an important design consideration because it was not desirable to have the vehicle power source cause degradation in on-board instrument and electronic components. **The RTG brick/thermoelectric converter configuration was the key design driver for the diameter of the vehicle.**

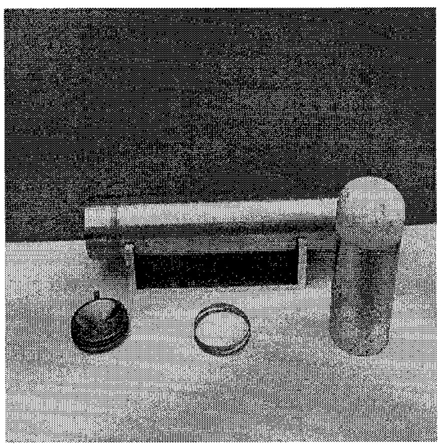
3. **Instrument Bay:** The instrument bay is 15–20 cm long and can house either several small science instruments (e.g., camera/microscope, UV LED/spectrometer, wet chemistry), or 3 instrument pods containing instruments like a multi-focal plane array and/or amino acid, DNA extraction chip(s). Melt-water sample is driven across a

porous membrane by the external pressure of the ice/water. Micro peristaltic pumps move the sample to the center core where it can then be distributed and analyzed by the various instruments in the bay.

4. **Avionics Bay:** The avionics bay contains the power conditioning/distribution board, acoustic imaging board, state sensors, instrument driver boards for controlling the instruments and storing data, the primary vehicle micro-controller, A/D, memory buffers, and communication driver board. Although the configuration shown in Figure 1 displays the boards mounted on an internal truss, current reconfiguration design work with the existing prototype shows that it is feasible to fit the respective board electronic components on wafers and mount the boards perpendicular to the axis of the vehicle. This configuration is much more volume efficient and provides more volume for additional components like the water jet pump and reservoir.

5. **Communication Bay:** The communication bay contains the primary vehicle transmitter/ receiver, and a series of mini-radiowave ice transceivers. The RF transceiver design is discussed later in this paper. The communication bay is 40 cm long with each transceiver only 3 cm thick by 10 cm in diameter. Each mini-transceiver is baselined to be powered by an RHU milli-watt power system. A shape-memory heat activated lever moves the transceiver stack up as each transceiver is ejected out the rear end of the vehicle. The transceivers refreeze in the slush plume behind the vehicle as the vehicle descends.

The complete operating cycle of the CHIRPS vehicle is discussed in the next section. Figure 2 shows the prototype vehicle that is being built to test and characterize probe melt dynamics; closed-loop, semi-autonomous control; and science instrument delivery, control, and operation. The reader should note that this vehicle **does not employ RTG power**, but uses a surface-based generator and tether to deliver power to the vehicle. This configuration is much more practical for field testing the vehicle system.



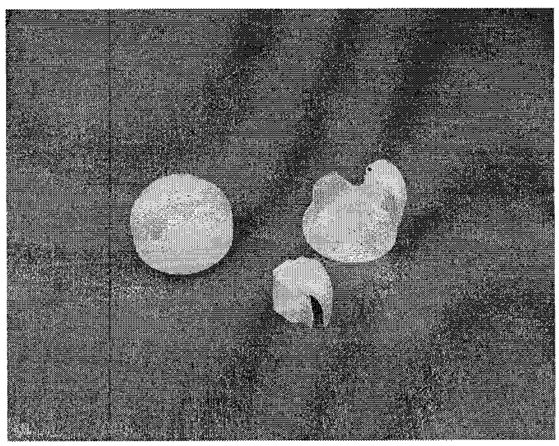


FIGURE 2. Prototype Cryobot Probe with Four-quadrant Nose.

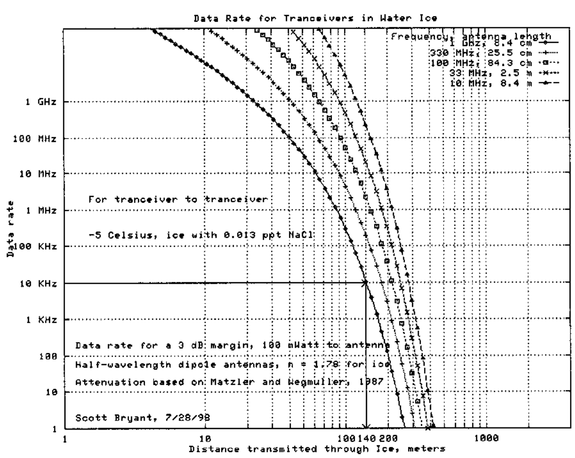
B. CHIRPS Operation on Europa

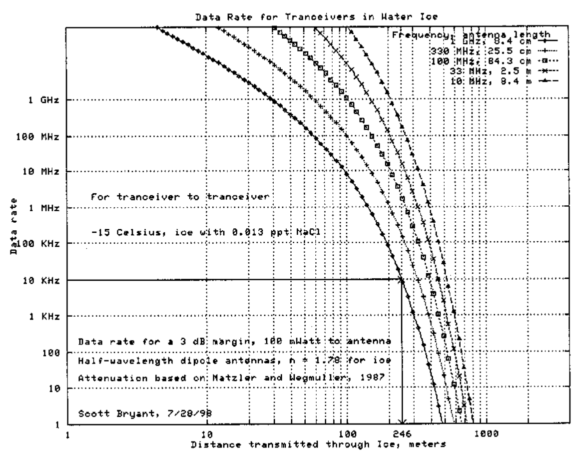
Once the Europa lander is on the surface, a gimbaled telescoping strut structure allows the probe to seek its own gravity vector as it is lowered to the surface. As CHIRPS initiates its thermal sublimation cycle, surface material sublimates into the Europan surface vacuum creating a void. The lander communication module sits on top of the probe and provides an additional axial pre-load to maintain a pushing force to keep the probe in contact with the ice. The communication module follows the probe into the ice and acts as a plug to stop the ice sublimation action, as well as let the ice protect the communication electronics from the intense Jovian radiation. A 20-cm diameter receiver/transmitter on the bottom of the avionics package snaps open before the void re-freezes. Once the probe is in the ice, the only lander elements remaining on the surface are the lander structure, orbiter relay antenna, and the umbilical connecting the antenna to the lander communication avionics.

With the ice void plugged by the communications module, the pressure inside the void increases and the probe can initiate its melt cycle. The forward-looking acoustic imager determines if there are any obstacles. If the ice is clear, all heat is diverted to the front of the four-quadrant nose where the melt void is created. As the ice moves through the solid-to-liquid phase change, the melt-water is displaced by the probe and the probe descends. If obstacles are encountered, the control system differentially activates the quad heaters on one side or the other to open up the melt void more on only one side of the vehicle. Shell heaters mounted near the rear of the vehicle are also activated to assist in creating a “tilted” melt column for the probe to follow.

As the vehicle descends, the mini-ice transceiver relays are deposited in the slush void behind the vehicle and allowed to refreeze. Figures 3 and 4 show the modeled projections for RF signal attenuation in ice using actual empirical data from Antarctica [5]. The data rate attenuation curves are displayed as a function of ice temperature and assumed impurities (i.e., saltwater). For a 1-GHz, 8.4-cm diameter antenna transmitting at a data rate of 10 KHz, the reader can see that the transmission distance almost doubles as the ice temperature goes from –5 °C to –15 °C. Indeed, as the ice temperature drops, ice acts as a good insulator and RF signals can transmit across much greater distances. Figure 5 shows the optimal relay drop-off intervals as a function of ice temperature and depth (note that for a 10-km penetration, the number of ice transceivers relays is on the order of 13 to 16—certainly a small enough quantity to fit within the reasonable volume constraint of a cryobot (see Figure 1).

The acoustic imager senses the ice-ocean interface and at approximately 100m above the interface, the combined nose, power bay, and instrument bay separate from the avionics bay. The avionics bay re-freezes in the ice and the front of the probe, attached by a tether to the avionics bay, continues to break through the ice and drop into the ocean. The instrument pods are released and passively float up to the ice-liquid interface to image and sample for bio-signatures. The complete deployment/melt sequence is shown in Figure 6.





FIGURES 3 and 4. RF signal attenuation in ice as a function of ice temperature and assumed impurities.

FIGURE 5. Optimal relay drop-off intervals as a function of ice temperature and depth.

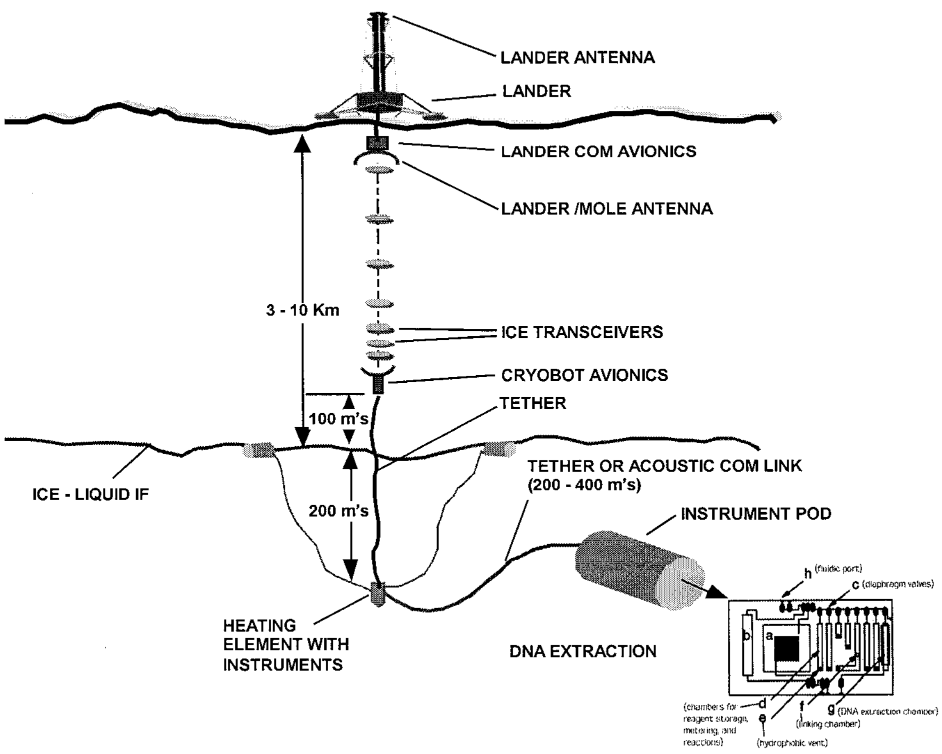


FIGURE 6. Complete deployment/melt sequence

3. ICE PENETRATION MODELING RESULTS

This section of the paper is not meant to be an exhaustive discussion of the fluid dynamics and energy modeling of the phase-change melt process. Most importantly, this section of the paper discusses the results of the fluid/thermal modeling and shows the results of laboratory tests to validate the model. Results of the fluid and heat transfer modeling showed that the most efficient way to create the phase change state from ice-to-water was to input just enough heat to initiate and sustain melt. Since water is a good insulator, raising the temperature significantly above freezing resulted in an increase in the melt-water jacket around the vehicle and a subsequent decrease in heat transfer to the actual ice-melt interface [6]. The model firmly established that for Europa, .6Kw thermal input did not provide enough energy to raise the ice temperature (–170 °C) sufficiently to initiate melt. The Europa ice is so cold it acts as an infinite heat sink and the heat is transmitted into the heat sink so quickly that localized phase change at the vehicle shell is impossible. Melt was initiated at 0.8Kw, but with no margin for error on the actual ice temperature. At 1Kw, phase change at the vehicle shell interface was sustainable with the creation of about a 1mm melt-water jacket around the vehicle [6]. With 1Kw of thermal energy put into initiating the phase change of ice-to-water, the vehicle was projected to melt at 0.5 to 1 m/hr. This would be approximately 10 m/day, leading to several kilometers over a year. The reader should be reminded that as the probe descends, the **ice temperature increases, allowing the probe to accelerate, thus giving a range on the descent rate.** Regardless of the exact depth, the model convincingly showed that a deep ice penetration of the Europa ice sheet was achievable with only 1 Kw of thermal energy.

The above modeling results were validated in the laboratory using a prototype probe of known geometry (frontal area equivalent to the model, i.e., 12 cm), ice with known properties (both ice structure and temperature, i.e., nominally –10 °C), and known energy input (1 Kw). The results of the laboratory tests showed significantly higher melt rates (i.e., > 1 m/hr) due to the warmer ice. However, when scaled to colder ice temperatures, the laboratory results showed good agreement with model results. Figure 7 shows actual and predicted melt rates for the cryobot as a function of ice temperature/pressure for a 1 Kw thermal energy source. Interestingly, the empirical results showed that heat loss through other channels (i.e., internal heat dissipation through the vehicle structure) did not allow "all" of the energy to be concentrated at the nose. As a result, Figure 7 shows a descent rate correction of 0.5 to 0.3 m/hr projected for Europa. Consideration is being given to increasing the power from 1 Kw to 1.25 Kw to compensate for other loses.

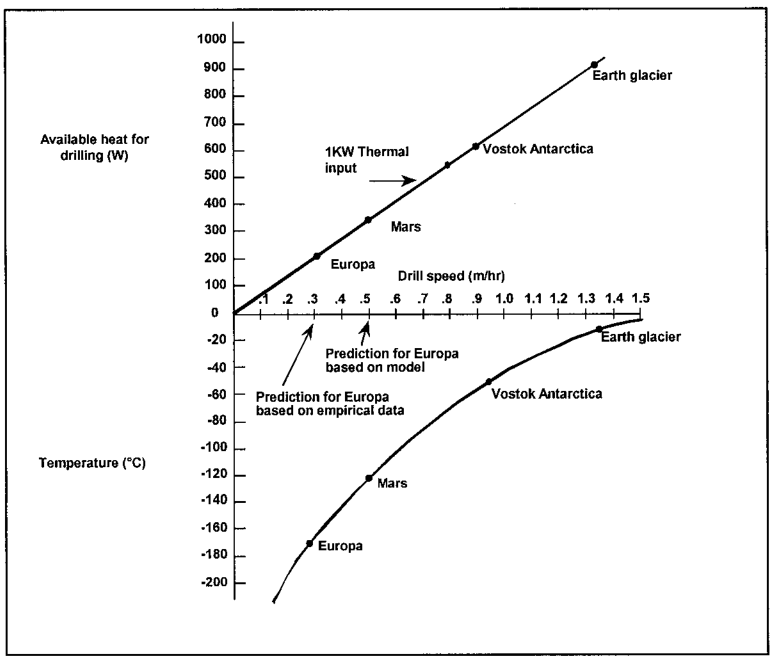


FIGURE 7. Actual and predicted melt rates for the cryobot as a function of ice temperature/pressure for a 1 Kw thermal energy source.

4. ICE COMMUNICATION MODELING RESULTS

As stated in the above problem statement, tethers and acoustic communication are not feasible in a dynamic, noisy ice environment. As a result, the CHIRPS team looked carefully at historical research done on the transmission of radio-waves through ice to determine if RF was a viable communication medium. It should be stated up front that the design work currently being done at JPL in this area of mini-radiowave ice transceivers is considered proprietary. Therefore, the reader will be provided the basis for determining the feasibility of using RF communication in ice with only a high level summary of the ice transceiver design. Maetzler, Wegmueller developed equations for real and theoretical permittivity of ice by doing a curve fit to actual measurements they made in the GHz region of the radio spectrum [7]. Their data matched other reasearchers results into the 100MHz region of the spectrum. The primary conclusion was that real permittivity is relatively insensitive to frequency in the GHz region but does vary with temperature. So as the temperature decreases, ice acts less as a conductor and the signal can penetrate a greater distance in the ice. One other physical element of ice containing impurities, which might aid the Europa problem, is that over a long period of time, and in the presence of thermal gradients, sea ice sheds brine and becomes more pure. Since salt impurities increase the conductivity, RF signals would be attenuated even further. Figures 3, 4, and 5 above provided a visual depiction of the extrapolated Maetzler, Wegmueller equations for the Europa RF signal penetration paradigm, and indeed, confirmed that RF signal transmission in ice was the proper communication avenue to pursue.

Based on the above model, the team proceeded to size the power system that would drive the ice transceivers [8]. Nominally, it is expected to drive 5 MB of data/day from the vehicle to the lander, for relay to the orbiter. Based on an acceptable trickle rate of 10 Kb/sec, 4000sec are required to transmit this data within a 24-hr period. Standard required transmission power levels are on the order of 120 mw minimum. By operating the receiver and transmitter out of phase (i.e., one is in sleep mode while the other is operating), it is possible to operate the complete system on 120 mw. However, considering typical 1w overhead for transmitter drive power, and standard 0.5 power amplifier efficiency, each transceiver actually needs about 1.3w total power in order to provide 120mw of transmit power. Unfortunately, small "watt" scale isotope power sources are not readily available—only milli-watt scale power sources are off-the-shelf. Therefore, the team developed a "burst" scheme for sending data from relay-to-relay. Using advanced capacitive storage devices, the milli-watt isotope power source trickle charges the on-board capacitors and during the transmit interval, the necessary 1.3w is converted into full transmit power [8]. The use of the milli-watt isotope power source turns out to be absolutely essential because the trickle charge process must be continuous in order for the communication duty cycle to be satisfied for the long term (i.e., over both the daily duty cycle and the one- to two-year mission life).

5. APPLICATION OF RADIOISOTOPE POWER SOURCES FOR MOBILITY AND COMMUNICATION

The above discussion provided the reader with the design foundation behind the CHIRPS mole penetrator. Once the power requirements were determined based on the respective vehicle melt and communication designs, the Department of Energy (DOE) was contacted and an isotope power support team was established to derive a compatible power and packaging design for both the RTG and milli-watt power stick radioisotope power sources. The following sections summarize the results of the DOE power design, cost, and availability tradeoff study.

A. CHIRPS Primary Power for Mobility/Electrical

The current baseline RTG design for CHIRPS vehicle is shown in Figure 8. To be conservative, it was decided to assume a Cassini general-purpose heat source (GPHS). This approach guaranteed technology availability by the 2005 timeframe, and met the power, mass, and packaging constraints of the vehicle design. The specifications are shown in Table 1.

B. CHIRPS Primary Ice Transceiver Power

The current baseline for ice transceiver power is the lightweight RHU (LWRHU) power system (i.e., 3 RHUs heat source with a thermoelectric converter). Again, in the analysis it was determined that 3 RHUs would provide the desired power and also meet the mass and packaging constraints of the current ice transceiver design (see Section 2). The specifications for the ice transceiver LWRHU is shown in Table 2.

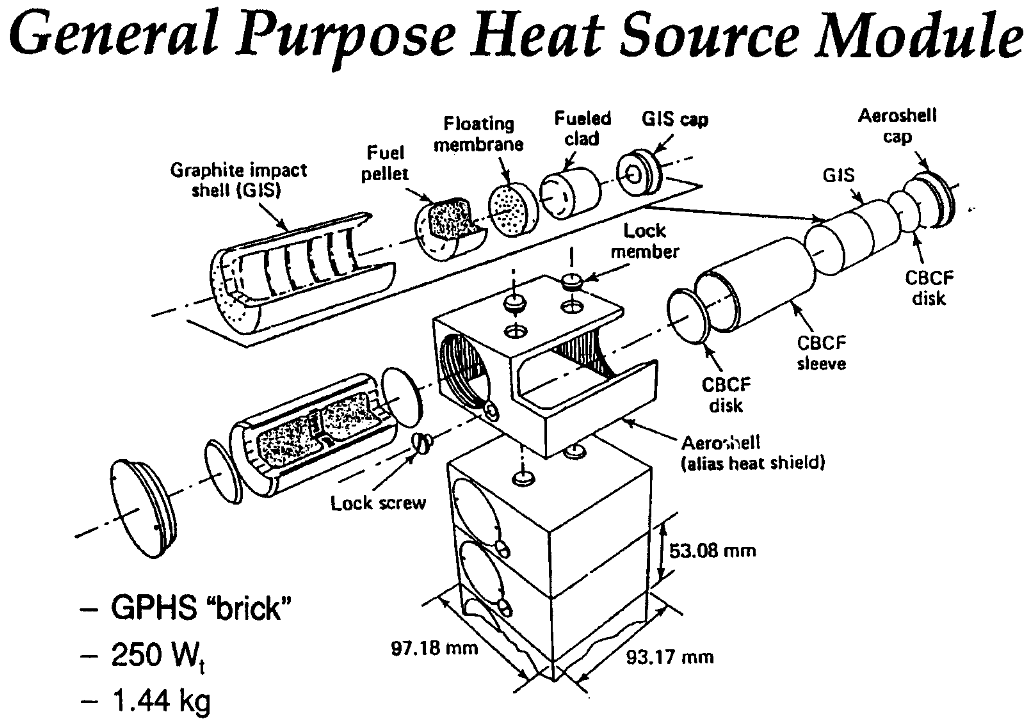


FIGURE 8. Current baseline RTG design for CHIRPS vehicle.

TABLE 1. Cassini Class RTG Specifications—CHIRPS Primary Mobility/Power Source.

RTG power level/GPHS	244 w thermal beginning of life (BOL)
Mass	1.44 Kg/GPHS
Material	Plutonium: 238 (7390 Curies)
Thermoelectric efficiency	6.4%
Number of GPHS rqrd	4 (maybe 5)
Approximate dimensions/GPHS	10 cm × 10 cm × 5 cm thick (15 cm across the diagonal)

TABLE 2. Cassini Class LWRHU Specifications—CHIRPS Ice Transceiver Power Source.

RTG power level/unit	1.1w thermal BOL

Mass	39.8 g/unit
Material	Plutonium 238 (32.8 Curies)
Thermoelectric efficiency	3–4% (giving the desired 30–40 mw/RHU)
Number of units rqrd/transceiver	3
Approximate dimensions/RHU	2 cm dia × 3 cm long

6. CONCLUSIONS

In conclusion, a careful design and selection of radioisotope power sources to enable both cryobot mobility and communications has been completed. Consideration was given to the state of readiness of radioisotope technology, required/available power, power conversion efficiencies, accommodation of existing packaging of the isotope devices, and how to protect vehicle internal electronic devices from the radioisotope material particle fluxes. At this time the current baseline design for the cryobot appears feasible from the standpoint of functionality and meeting launch volume and mass constraints. As stated in the abstract, any use of a radioisotope powered cyrobot for Mars or Europa will meet environmental and planetary protection requirements.

7. ACKNOWLEDGEMENTS

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